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Skin penetration surrogate for the evaluation of less lethal kinetic energy munitions

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ABSTRACT

Although the benefits of the use of less lethal kinetic energy munitions are numerous, there is a need to evaluate the munitions prior to deployment to ensure their intended effect. The objective of the current research was to validate a surrogate that could be used to predict the risk of penetration of these devices. Existing data from biomechanical testing with post-mortem human specimens (PMHS) served as the foundation for this research. Development of the surrogate involved simulating the various layers of the skin and underlying soft tissues using a combination of materials. A standardized 12-gauge impactor was used to assess each combination. The energy density that resulted in a 50% risk of penetration for the anterior thorax region (23.99 J/cm^2) from the previous research was matched using a specific combination of layers. Twelve various combinations of materials were tested with the 50% risk of penetration determined. The final validated surrogate consisted of a Laceration Assessment Layer (LAL) of natural chamois and .6 cm of closed-cell foam over a Penetration Assessment Layer (PAL) of 20% ordnance gelatin. This surrogate predicted a 50% risk of penetration at 23.88 J/cm^2. Injury risk curves for the PMHS and surrogate development work are presented.

1. Introduction

The ability to evaluate injury potential of less-lethal kinetic energy (KE) munitions has been an ongoing goal in the ballistics community for a number of years [1,2]. The goal of less-lethal KE rounds is to deter an individual without causing serious or even fatal injury using blunt impact force. However, several cases of less-lethal KE munitions penetrating into the body have been reported and the result has been serious injuries or death [3–6]. Therefore, there exists a need to develop a biofidelic skin penetration surrogate for the less-lethal community so that KE munitions can be evaluated prior to deployment in the field.

Over the years a number of different ballistic injury surrogates have been utilized: soap, gelatin, clay, animals, post-mortem human subjects (PMHS), and other materials. Certain simulants, such as soap and clay, are inelastic and provide a permanent deformation cavity. Although they provide the ability to maintain a permanent record and determination of energy transfer, they lack the visco-elastic nature of human tissue [7]. Their role in ballistic studies involving penetrating rounds has been established [8]. However, the risk of penetration, rather than the temporary and permanent cavities of the bullet path, is a key assessment factor in less-lethal KE munitions. This is especially true of smaller caliber munitions, such as 12-gauge rounds. Therefore, the role of the current surrogates is limited as it relates to the assessment of the penetration of tissues with less-lethal KE munitions.

A previous study, using PMHS [9], assessed the skin penetration qualities of human tissue over various regions of the body. Eight unembalmed PMHS were impacted with a 12-gauge, fin-stabilized, rubber projectile to simulate loading conditions representative of those seen with less-lethal KE munitions. Each specimen sustained impacts to the anterior and posterior thorax, abdomen, and legs. For each impact, the energy density (E/a) was calculated and injury was determined according to three outcomes: no injury, laceration, and penetration. Based on these results the energy density required to achieve a 50% probability of skin penetration for each region of the body was determined using binary logistic regression.

As observed in the previous testing, the anterior torso exhibited different skin penetration qualities when comparing areas over bone, such as the ribs, and areas without underlying bone, such as between two ribs. Impacts on bone were found to have a 50% probability of penetration at 23.99 J/cm^2 while areas without underlying bone were found to have a 50% probability of penetration at 33.30 J/cm^2. Since it is not feasible for law enforcement personnel to only target areas without underlying bone, the more conservative value of 23.99 J/cm^2 should be chosen for surrogate development [9].

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Using the energy density results from Bir et al. [9], the current study was conducted to identify an appropriate skin penetration surrogate for use in the evaluation of less-lethal KE munitions. In order to achieve similar skin penetration results, a multi-layered model was chosen to represent skin, subcutaneous fat, and underlying tissue and organs. The anterior region was identified for skin penetration surrogate development due to this area having the lowest energy density threshold and it serving as the typical region for shot placement.

2. Materials and methods

A multi-layer approach was taken for the development of the skin surrogate model. This approach involved modeling each layer of the skin and underlying tissues as a separate entity and combining them into a final surrogate. An underlying layer to represent the soft tissues such as the muscle and fat which was called the Penetration Assessment Layer (PAL), covered by a Laceration Assessment Layer (LAL) used to simulate the skin (Fig. 1). Several materials were tested in combination in an effort to identify the best combination of materials.

For all potential models, 20% ordnance gelatin was used as the Penetration Assessment Layer (PAL). The testing was conducted with ordnance gelatin 250 Type A Ordnance Gelatin (Gelita USA) using a preparation and calibration method previously used in less lethal [1] and body armor [10] studies. The gelatin was prepared in a 20% concentration by mixing 20 parts *by weight* of the ordnance gelatin with 80 parts *by volume* of 82-degree Celsius water. Cinnamon oil was added to the water before the gelatin was added in order to decrease foaming and inhibit mold. The mixture was allowed to stand for approximately 1 h before being poured into a 100 mm by 100 mm by 150 mm aluminum pan (Wilton, Woodridge, IL, part 2105-1588). The pan was then placed in an environmental conditioning chamber at 10-degrees Celsius for 24 h prior to use. This procedure is based on previous work conducted by Prather [11]. Gelatin was calibrated prior to testing with 0.177 caliber copper-plated sphere BBs fired at 179 ± 4.5 m/s. The muzzle to block distance was 3.05 m. The penetration distance was measured with digital calipers and recorded. For this assessment, acceptable penetration depth was defined as 3.81–7.62 cm (1.5–3.0 in).

Several materials were evaluated for purposes the outer assessment layers, termed the Laceration Assessment Layers (LAL). These materials include closed cell foam (five varying types), leather, vinyl, and natural chamois. The surrogate preparation included placing the gelatin block on an adjustable height table. Elastic straps with clips attached to the ends were used to secure the LALs to the gelatin. Fig. 2 shows an example of the surrogate apparatus.

The test methodology was similar to the previous PMHS skin penetration study [9]. A 12-gauge, fin-stabilized, rubber rocket round was used as the impactor for all of the tests conducted (Fig. 3). The amount of gunpowder used during assembly of the munitions was varied to achieve the desired velocities and the rounds were fired from a distance of 1.5 m using a universal receiver. Velocity measurements were recorded using a chronograph placed 0.55 m from the target. All testing was recorded using high speed video at 20,000 frames per second.

Following each impact to a given location a visual inspection of the surrogate was performed. Perforation of the outmost layer(s) and the presence of a permanent cavity in the ordnance gelatin were noted. The results was defined in the following manner: "no injury" if both the round failed to perforate the outer layer and no permanent cavity occurred in the gelatin, "laceration" if the outer layer was perforated but the gelatin did not possess a permanent cavity, and "penetration" if both the outer layer was perforated and the gelatin possessed a permanent cavity. Following visual inspection, energy density was calculated using the round's mass and diameter. The use of energy density has been established as a means to measure a projectile's ability to penetrate human tissue [12,13].

To compare the energy density results of the surrogates and to perform binary logistic regression analysis, it was necessary to achieve both penetrating and non-penetrating results with each combination of materials. Therefore, an initial test was conducted for a given combination. If penetration occurred, subsequent testing was completed at decreasing velocities until no penetration occurred. If the initial test did not result in a penetration, subsequent testing was conducted at increasing velocities until penetration did occur.

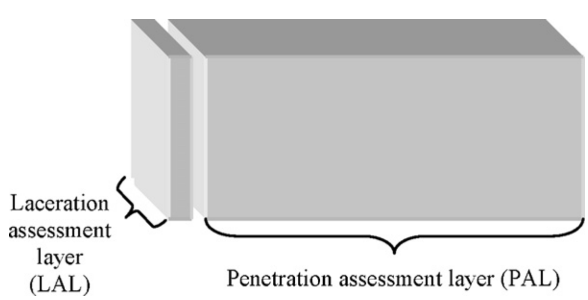

Fig. 1. Multi-layer approach to development of skin surrogate.

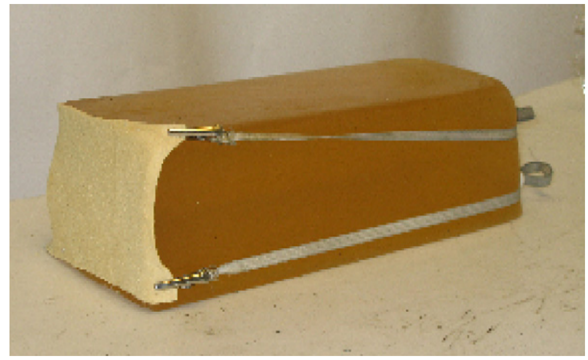

Fig. 2. Test setup for evaluation of both LAL and PAL materials.

Once an assessment of the surrogate was completed, the results were evaluated in terms of injury to the surrogate. The result was categorized as "1" if damage occurred to the PAL (gelatin) and "0" if no damage to the PAL was observed. In an effort to determine the predictive capability of the model, logistic regression was performed on the data. The use of logistic regression provides the ability to determine the relationship between the probability of an event occurring (injury) and the value of an independent variable (engineering parameter). When examining the data, the dichotomous state of occurrence versus nonoccurrence can be established for the dependent variables. The continuous values of the physical parameters serve as the independent variables in this type of analysis. The result is a sigmoidal cumulative distribution function being fit to the data. The general function for this curve is:

$$P(x) = \frac{1}{1 + \exp(-\alpha - \beta X)}$$

where $P(x)$ is the probability that the dependent variable will occur as a function of the independent variable X, where α and β are the best-fit parameters for a sigmoidal response to the dichotomous data.

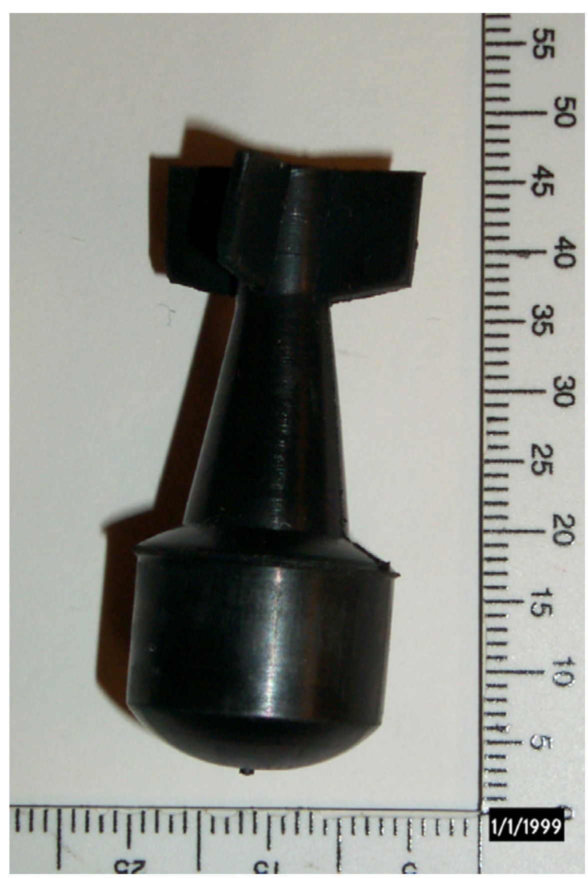

Fig. 3. Impactor used to evaluate surrogate.

Table 1
Results of varying materials used for LAL.

LAL[a]	PAL	α	β	(E/a)
None	Gelatin	−66.12	4.67	14.46
C	Gelatin	−107.28	6.24	17.18
C-C	Gelatin	−77.38	4.25	18.19
C-F1	Gelatin	−156.78	6.56	23.88
C-F3	Gelatin	−188.22	7.77	24.24
C-F3-C	Gelatin	−103.18	3.24	31.84
L-F3	Gelatin	N/A	N/A	Over 44.03
C-F1-D-F2	Gelatin	−78.56	1.83	43.02
C-F4	Gelatin	−109.57	4.13	26.54
C-F4-C	Gelatin	−21.089	0.556	37.93
C-F5	Gelatin	−321.46	9.19	34.99
Vinyl	Gelatin	N/A	N/A	Below 14.98
PVA	Gelatin	N/A	N/A	Below 16.62

[a] C- chamois, L- leather, F1- 0.6 cm foam, F2- 0.3 cm foam, F3- 0.93 cm foam, F4- 3–4 lb/ft^3 foam, F5- 7–8 lb/ft^3 foam.

Logistic regression was then performed using SPSS software. A binary logistic regression analysis uses an independent variable to create a function that serves as a predictor for the probability of an occurrence. As in the original study, energy-density was chosen as the parameter for the prediction of penetration. Using the results of the SPSS analysis, logistic curves were generated and the 50% risk was determined.

3. Results

A baseline assessment was first completed without the use of a LAL layer. The penetration threshold of the gelatin devoid of any outer layer was found to be 14.17 J/cm^2. Once this baseline test was completed, various outer layers were assessed with the inner gelatin layer. These include single and double layers of chamois, leather, vinyl, polyvinyl acetate (PVA), 0.3 cm closed cell foam, 0.6 cm closed cell foam, and 0.9 cm closed cell foam. The logistic regression results, including α and β values and the energy density threshold (50% risk) can be found in Table 1.

Based on the results in Table 1, the most appropriate surrogate for the anterior torso was found to be a LAL consisting of an outer layer of natural chamois and an inner layer of 6 mm thick closed cell foam (Darice Inc., part number 1199-20). The two distinct layers of the LAL are secured to the 20% ordnance gelatin PAL. This surrogate predicted a 50% risk of penetration at 23.88 J/cm^2. A comparison of the penetration risk curves for the human cadaveric assessment found by Bir et al. [9] and the proposed surrogate for the anterior torso can be found in Fig. 4.

4. Discussion

Currently, the most popular tissue simulant utilized in the ballistics industry is ordnance gelatin. This penetration model reacts similar to live tissue during bullet penetration [14]. A temporary cavity is formed as the bullet passes through the tissue,

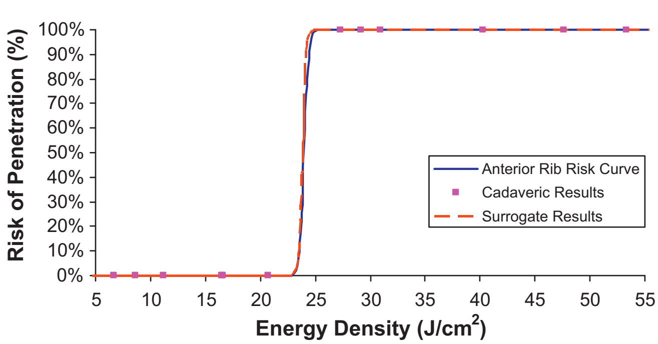

Fig. 4. Comparison of penetration risk curve of anterior thorax found by Bir et al. [9] versus proposed surrogate.

which then collapses leaving a permanent wound cavity. Twenty-percent gelatin tested at 24 °C was first utilized in 1962 [15]. However, it was found to have a greater depth of penetration than live tissue [16]. Fackler and Malinowski [14] developed a testing methodology of 10% gelatin at 4 °C. It was found that this testing regimen produced results that were accurate to within 3% of the testing conducted on live tissue. A gelatin block of 25 cm × 25 cm × 50 cm that was maintained at 4 °C provided for the accuracy of these results [14].

One of the more recent advances in ballistic surrogates is a multi-dimensional approach. One example, called the "skin-skull-brain" model [17], was used to study wound ballistics with respect to gunshots to the head. The model consisted of a silicone cap (skin), polyurethane shell (skull) and ordnance gelatin (brain). Although this model successfully exhibited wound patterns similar to a gunshot wound to a human skull, its repeatability was not demonstrated. In addition, this model is limited to impacts to the skull. Another recent approach utilized ballistic gelatin and cowhide as a ballistic skin stimulant [18]. This approach used threshold velocity to compare the proposed stimulant with previously reported values to specific body regions.

A surrogate for non-ballistic blunt force trauma was recently developed using the multi-layer approach [19]. This model used an open-celled foam representing the sub-dermal tissues which was covered by a silicone layer representing the skin. Comparisons were made to case studies where wounding was caused by blunt impacts. The researchers noted that disruption of the underlying foam was possible without laceration of the silicone layer and speculated this represented damage to underlying tissues such as that seen in bruising. This correlates well with the current effort where damage was at times noted in the PAL without obvious tearing of the LAL.

Although the proposed surrogates exhibited the same energy density characteristics as the PMHS study, there exist both advantages and disadvantages to using such surrogates. First, the penetration properties of the surrogate are based on a 50% probability of penetrating human skin. Therefore, a round that has a calculated energy density below the 50% threshold may still be capable of producing a penetration. This is merely an indicator of risk of penetration. In addition, the surrogates were selected to exhibit pass/fail characteristics at the 50% threshold. Different surrogates would be required to evaluate munitions at a 25% or 75% risk of penetration.

The slopes of the surrogate risk curve in Fig. 4 show the pass/fail nature of the surrogate as well as its repeatability, however, several points of discussion remain. First, the energy densities used in this study are based on the results of the PMHS testing. Although the results for the thoracic region were statistically significant, variation occurs in skin thickness of different individuals. Therefore, it is possible that rounds could penetrate one individual but not another for a given energy density. However, it is believed that the use of elderly subjects would represent a conservative approach.

It should be noted that natural chamois is highly variable in thickness, thus various samples of assorted thickness may lead to slightly different results. The chamois used for the suggested simulants were within the range of 0.115 cm and 0.180 cm with the optimal target thickness of 0.139 cm based on the average thickness of the chamois tested.

Another point of discussion is the presence of clothing. The PMHS tests in the original study were conducted in the absence of clothing. Manufacturing rounds based on evaluations using this skin surrogate may be too conservative when attempting to deter an individual with heavy clothing or multiple layers of clothing. However, it is also necessary to provide adequate injury mitigation to those individuals who are not wearing clothes at the time of the

incident such as an individual not wearing a shirt or one who is wearing shorts.

5. Conclusions

One of the main goals of this effort was to introduce a repeatable, cost-effective surrogate to evaluate less-lethal kinetic energy rounds. Based on the results of PMHS testing, it was found that the use of multi-layered surrogates provided the most biofidelic results. Evaluation of rounds can occur using a simple pass/fail criterion (penetration/no penetration) in place of mathematical calculations. Therefore, such a tool can be a valuable asset to less lethal manufacturers during munition development, law enforcement agencies during less lethal product selection, and government agencies during the development of recommendations and test standards.

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References

[1] C.A. Bir, The Evaluation of Blunt Ballistic Impacts of the Thorax, in Bioengineering, Wayne State University, Detroit, 2000.
[2] H. de Freminville, et al., Less-lethal hybrid ammunition wounds: a forensic assessment introducing bullet-skin-bone entity, J. Forensic Sci. 55 (5) (2010) 1367–1370.
[3] A. Charles, et al., Penetrating bean bag injury: intrathoracic complication of a nonlethal weapon, J. Trauma 53 (5) (2002) 997–1000.
[4] T. Olivas, B. Jones, M. Canulla, Abdominal wall penetration by a police "bean bag", Am. Surg. 67 (5) (2001) 407–409.
[5] P.A. Wawro, W.R. Hardy, Penetration of the chest by less-than-lethal "beanbag" shotgun rounds, J. Trauma 52 (4) (2002) 767–768.
[6] J. Suyama, et al., Injury patterns related to use of less-lethal weapons during a period of civil unrest, J. Emerg. Med. 25 (2) (2003) 219–227.
[7] B. Janzon, Projectile–material interactions: simulants, in: G.J. Cooper, H.A.F. Dudley, D.S. Gann (Eds.), Scientific Foundations of Trauma, Oxford University Press, 1997, pp. 26–52.
[8] K.G. Sellier, B.P. Kneubuel, Wound Ballistics and the Scientific Background, 1st ed., Elsevier, Amsterdam, 1994.
[9] C.A. Bir, S.J. Stewart, M. Wilhelm, Skin penetration assessment of less lethal kinetic energy munitions, J. Forensic Sci. 50 (6) (2005) 1426–1429.
[10] M. Wilhelm, A biomechanical assessment of female body armor, in: Biomedical Engineering, Wayne State University, Detroit, 2003.
[11] R.N. Prather, C.L. Swann, C.E. Hawkins, Backface Signatures of Soft Body Armors and the Associated Trauma Effects, Chemical Systems Laboratory, Aberdeen Proving Ground, MD, 1977, p. 40.
[12] V.J.M. DiMaio, Penetration and perforation of skin by bullets and missiles. A review of the literature, Am. J. Forensic Med. Pathol. 2 (2) (1981) 107–110.
[13] V.J.M. DiMaio, et al., Minimal velocities necessary for perforation of skin by air gun pellets and bullets, J. Forensic Sci. 27 (4) (1982) 894–898.
[14] M.L. Fackler, J.A. Malinowski, The wound profile: a visual method for quantifying gunshot wound components, J. Trauma-Injury Infect. Crit. Care 25 (6) (1985) 522–529.
[15] E.N. Harvey, et al., Mechanism of wounding, in: J.B. Coats (Ed.), Wound Ballistics, U.S. Army Surgeon General, Washington DC, 1962, pp. 143–235.
[16] C.E. Peters, A mathematical model of wound ballistics, J. Trauma (China) 6 (1990) S10–S15.
[17] M.J. Thali, et al., The "skin-skull-brain model": a new instrument for the study of gunshot effects, Forensic Sci. Int. 125 (2–3) (2002) 178–189.
[18] J. Jussila, et al., Ballistic skin simulant, Forensic Sci. Int. 150 (1) (2005) 63–71.
[19] K. Whittle, et al., The biomechanical modelling of non-ballistic skin wounding: blunt-force injury, Forensic Sci. Med. Pathol. 4 (1) (2008) 33–39.